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Thermal Performance Analysis of a High-Mass Residential Building

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THERMAL PERFORMANCE ANALYSIS OF A HIGH MASS RESIDENTIAL BUILDING

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ABSTRACT

Minimizing energy consumption in residential buildings using passive solar strategies almost always calls for the efficient use of massive building materials combined with solar gain control and adequate insulation. Using computerized simulation tools to understand the interactions among all the elements facilitates designing low-energy houses. Finally, the design team must feel confident that these tools are providing realistic results.

The design team for the residential building described in this paper relied on computerized design tools to determine building envelope features that would maximize the energy performance [1]. Orientation, overhang dimensions, insulation amounts, window characteristics and other strategies were analyzed to optimize performance in the Pueblo, Colorado, climate. After construction, the actual performance of the house was monitored using both short-term and long-term monitoring approaches to verify the simulation results and document performance.

Calibrated computer simulations showed that this house consumes 56% less energy than would a similar theoretical house constructed to meet the minimum residential energy code requirements. This paper discusses this high-mass house and compares the expected energy performance, based on the computer simulations, versus actual energy performance.

1. TIERRA CONCRETE HOUSE

Tierra Concrete Homes constructed the concrete house described in this paper near Pueblo, Colorado, where there are 5413 (3007) heating degree-days, 973 (540) cooling degree-days (65°F (18°C) base) and the average daily solar radiation incident on an unshaded horizontal surface is 1570 Btu/ft^2/day (17835 kJ/m^2/day) [2]. The house is an 1870-ft^2 (174-m^2) single-story, three-bedroom ranch. The entire exterior and most of the interior walls are pre-cast concrete. Two inches (5 cm) of polyisocyanurate insulation with an Exterior Insulation and Finish System (EIFS) covers the exterior walls.

1.1 Construction Method

Most of the exterior and interior walls were poured off site and transported to the building location, where a crane lifted them into place. The pre-cast walls included openings for doors, windows, electrical conduit, and outlet boxes. All interior wall surfaces were finished to look and feel like drywall. The roof is constructed with raised-heel trusses, drywall ceiling, and blown-in fiberglass insulation.

1.2 Construction Costs

At \$75/ft^2 (\$807/m^2), excluding land, the cost of this passive solar concrete home is similar to that of other custom homes in the area, which cost \$75 to \$82/ft^2 (\$807 to \$883/m^2). The costs of insulation (wall and slab perimeter) and the concrete walls are higher than that of typical wood-frame construction. However, significant savings are achieved through reduced construction time, limited use of drywall, and no central heating or cooling systems. A thermostatically controlled propane-fired stove provides heat for the master suite and a thermostatically controlled propane fireplace heats the main portion of the house. These units replaced the conventional heating, ventilation, and air-conditioning (HVAC) system and related ductwork that is found in most single-family houses.

2. PREDICTED PERFORMANCE

An hourly building-energy simulation tool was used during the design phase to optimize energy consumption [3]. All design decisions made to improve the house energy performance were compared to a base-case model that complied with the 1996 Home Energy Rating System (HERS) and the 1995 Model Energy Code (MEC) [4,5].

Four house models are used for comparison in this paper: the base-case , pre-construction , as-built, and calibrated. The base-case house was modeled as slab-on-grade, wood-frame construction with a footprint equal to the actual Tierra house. This base-case house was solar neutral (equal glazing areas on all orientations) to evaluate the impact of passive solar technologies.

A pre-construction model represented the optimized design. All interior load schedules and temperature setpoints were assumed the same in the base-case and pre-construction models.

The as-built model reflects changes to the pre-construction model as a result of differences incurred during construction. The as-built model was calibrated to more closely match measured data resulting in the calibrated model.

Table 1 provides envelope characteristics for the base-case house and Tierra as-built house. Figure 1 shows the simulated base-case and pre-construction heating and cooling loads. The total load predicted for the pre-construction design is 69.5% lower than the base-case house. Pre-construction model heating and cooling loads are 66% and 90% less than the base case, respectively. The minimized cooling loads eliminated the need for a cooling system.

TABLE 1: BASE CASE AND TIERRA DESIGN SPECIFICATIONS

Component	Base Case	Tierra
Infiltration	0.67 ACH	0.2 ACH
Wall R-Value	17.2 ft^2·°F·hr/Btu (3.0 m^2·K/W)	14 ft^2·°F·hr/Btu (2.5 m^2·K/W)
Roof R-Value	35.2 ft^2·°F·hr/Btu (6.2 m^2·K/W)	38 ft^2·°F·hr/Btu (6.7 m^2·K/W)
Floor R-Value	4.5 ft^2·°F·hr/Btu (0.8 m^2·K/W)	8 ft^2·°F·hr/Btu (1.4 m^2·K/W)
Window U-value	0.4 Btu/ft^2·°F·hr (2.3 W/m^2·K)	0.38 Btu/ft^2·°F·hr (2.2 W/m^2·K)
Window SC (summer/ winter)	0.7/0.89	0.8
Internal Mass	8 lb/ft^2 (39 kg/m^2)	100 lb/ft^2 (488 kg/m^2)

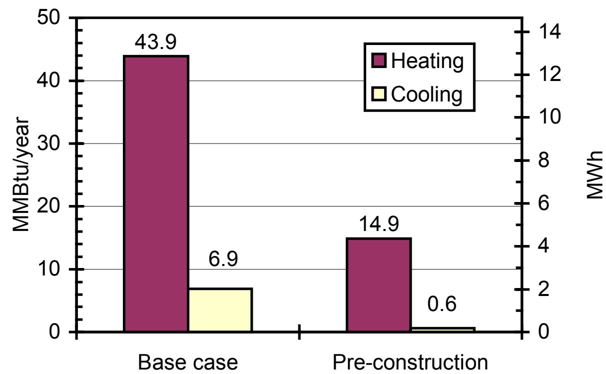

Fig. 1: Base-case and pre-construction model energy load comparison.

3. DESIGN CHARACTERISTICS

The concrete construction with exterior insulation resulted in extremely air-tight construction (0.2 ACH)[6]. This infiltration rate translates to about 62 cfm (29 L/s), which satisfies residential construction ventilation requirements [7].

The house design is engineered to maximize winter solar gain. A long east-west axis allows 80% of the glazing to be on the south side of the house. The high shading coefficient (SC) glazing maximizes the solar gains that enter the house during the winter. Overhangs were sized to block unwanted summer solar gains.

Lighting loads were reduced through extensive use of daylighting and installation of compact fluorescent fixtures. A clerestory with an east/west axis brings daylighting deep into the northern half of the house.

The use of daylighting, energy-efficient lighting, and overhangs has the added benefit of reducing summer cooling loads. Nighttime natural ventilation pre-cools the interior mass (concrete walls and floor) to further offset cooling loads. Opened clerestory windows promote the stack effect throughout the house to exhaust hot air and bring in cool outdoor air at night.

The thermal capacitance of the concrete walls and floor stores heat during the day in the winter and releases it at night. In summer, nighttime ventilation cools the mass. The mass remains cool throughout the day because the engineered overhangs minimize the solar gains. The ability of concrete to store heat or remain cool minimizes equipment loads during both heating and cooling seasons.

4. POST CONSTRUCTION PERFORMANCE VERIFICATION

Short-Term Energy Monitoring (STEM) tests were conducted after construction was completed [8,9]. After six days of testing, the building's thermal parameters were identified. These parameters were then used to extrapolate long-term energy performance. Test data were collected while the house was unoccupied to eliminate occupant-behavior effects.

STEM test results indicated that the actual solar gains were 27% less than that predicted by the pre-construction simulation. It was determined that this difference was primarily due to the glazing area in the as-built house being 7.6% less than in the pre-construction design, and that window screens had a much larger effect on solar gains than originally estimated. Adjusting the glazing area and adding "screens" with a SC of 0.70 to all windows calibrated the pre-construction model results to more closely match the measured short-term performance (Figure 2).

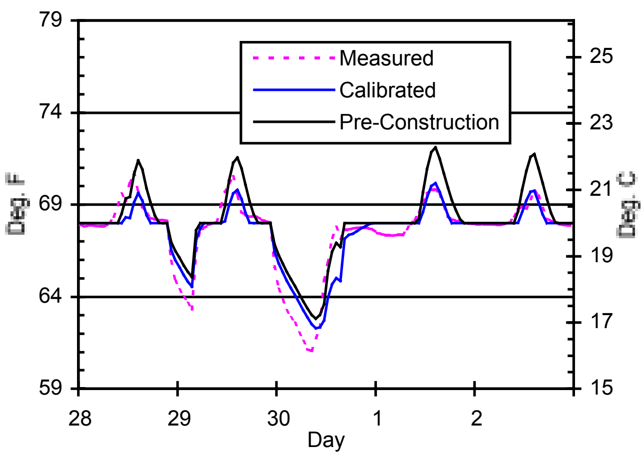

Fig. 2: Modeled and measured indoor temperatures at the end of November and beginning of December, 1996.

The calibrated model predicted annual heating and cooling loads of 22.40 MMBtu (6.57 MW·hr) and 0.04 MMBtu (11.7 kW·hr), respectively. This is a 56% savings compared to the base-case model, less than the 69.5% that was originally anticipated from the pre-construction design analysis.

Figure 3 shows where the calibrated model identified heat loss sources. These results show that heat loss through the slab is a primary concern, followed by heat loss through the windows and walls.

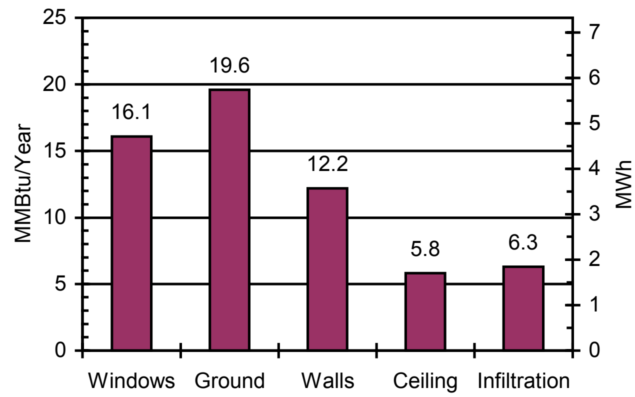

Fig. 3: Segregated heat loss for calibrated model.

The Tierra house was designed with perimeter slab insulation, as is conventional in the residential sector. Performance monitoring indicates that the entire slab should have been insulated. As improvements are made in other areas of residential building design and construction, heat loss paths that in the past were of minor concern become primary issues to reaching energy efficiency goals. The large percentage of total building heat loss through the slab in the Tierra house is an example of this situation.

The calibrated model also revealed that 30.3 MMBtu/year (8.9 MWh) of the heat gain is from passive solar gains (Figure 4). This accounts for 50% of the total heat provided to the house.

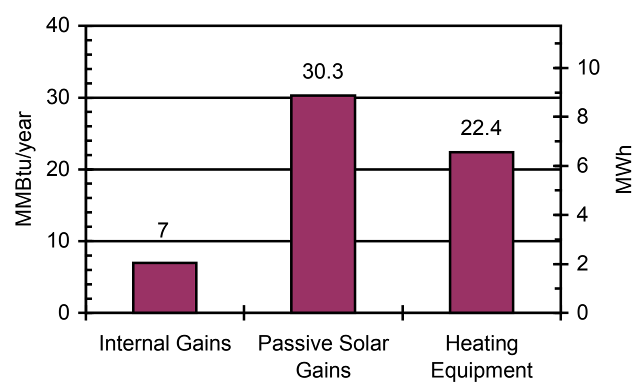

Fig. 4: Calibrated model heat sources.

5. DATA INTERPRETATION

Figure 5 shows indoor and outdoor temperatures, with the heating system off, during the coldest month of the long-term monitoring period. During four consecutive days of subzero outdoor temperatures (−18°C), the interior space temperature only dropped to about 48°F (9°C) even though there was no mechanical heat during this period. Surviving this strenuous test shows that the passive solar heating design of the house is freeze resistant, making the house resistant to disaster in a prolonged utility outage. The ability to minimize exposure to natural disasters limits insurer's liability for passive solar houses and is a side-benefit of passive solar design [10].

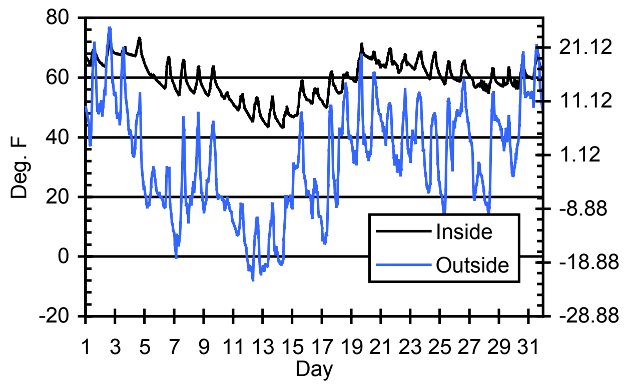

Fig. 5: January inside and outside temperatures with heating system off.

Long-term data collected while the house was unoccupied only partially demonstrates how the house can maintain comfortable summer indoor temperatures. The passive solar design depends on nighttime ventilation to pre-cool the massive concrete walls and floors. In the morning, the occupant closes all windows to prevent hot daytime air from entering the house. The cool walls and floors maintain comfort throughout the day. During the summer monitoring period, without the nighttime venting to precool the mass, the indoor temperature was above the normal comfort level but never exceeded 88°F (31°C) when outdoor temperatures were at their highest in the monitoring period, near 110°F (43°C). Using the calibrated model, the predicted indoor temperature when nighttime venting occurred was estimated to be about 10°F (6°C) cooler during this same period and never exceeded 78°F (26°C).(Figure 6)

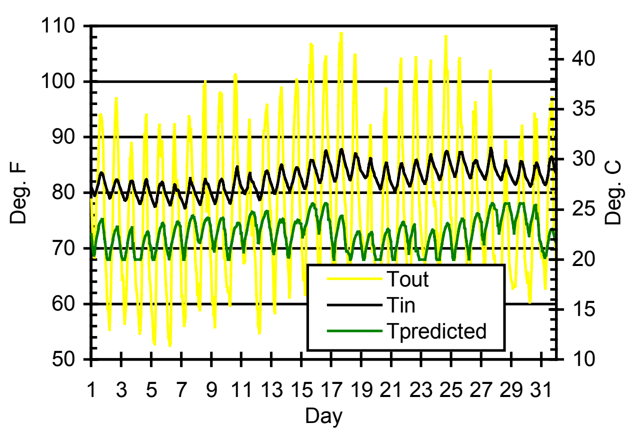

Fig. 6: July inside and outside temperatures and predicted inside temperature if nighttime venting is used.

6. IMPROVING THE PERFORMANCE

The calibrated simulation of the Tierra house was revisited to learn what design changes were necessary to achieve 70% energy savings while accounting for the lower solar gains. It was found that significant improvements could be achieved by increasing the wall and floor insulation. Simulations show that adding 1 in (2.5 cm) of wall insulation for a total of 3 in (7.5 cm) (R-21 ft^2·°F·hr/Btu [3.7 m^2·K/W]) and insulating the entire slab with 2 in (5 cm) of foam insulation (R-10 ft^2·°F·hr/Btu [1.8 m^2·K/W]) achieves the goal.

The improved design has a total heating load of 14.7 MMBtu (4.3 MW·hr) per year and a cooling load of 0.3 MMBtu (82.1 kW·hr) per year, 70.4% less than the base case. Figure 7 shows that the two largest heat losses are through the windows and floor. Using windows with lower U-values can reduce window heat loss; however, this reduces the SC resulting in lower solar gains. Simulations showed that the windows with the specified U-value and SC provided the smallest heat load based on this trade-off. The ground heat loss could be reduced with increased insulation levels, but this might not be practical or cost effective.

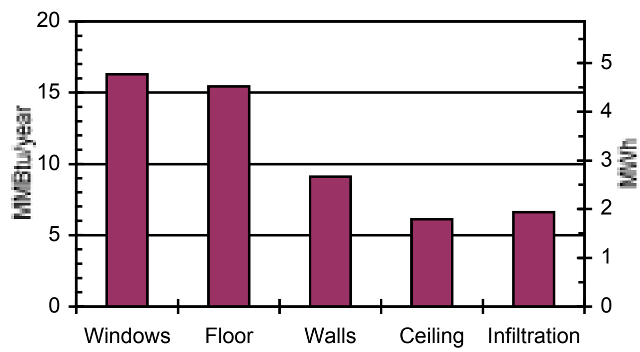

Fig. 7: Primary heat loss paths in improved design simulation.

7. CONCLUSIONS

In this climate, incorporating massive building materials is an effective strategy for ensuring smaller diurnal indoor temperature swings in low-energy residential building designs. The mass can store passive solar gains during the heating season and the pre-cooled mass can maintain comfortable indoor conditions during the cooling season.

Massive building construction most effectively improves comfort during the cooling season only when the mass can be pre-cooled at night. If the mass cannot be pre-cooled, then it is likely that the indoor temperatures will be higher than a comfortable level during the summer. It is also important that the mass be located within the conditioned space and insulated on the exterior.

The performance of passive solar buildings is sensitive to the amount of solar energy transmitted into the building. In this study the transmitted solar radiation was overestimated, and the slab heat loss was underestimated, resulting in an optimized wall insulation of 2 in (5cm) (R-14 $ft^2 \cdot °F \cdot hr/Btu$ [$2.5\ m^2 \cdot K/W$]). Good information on the shading coefficient of screens is generally not available. Also, accurate modeling of ground coupled heat transfer is difficult in all of the current generation of whole building simulation programs. Improvements in these two modeling areas would help in better optimizing very low energy buildings.

The Tierra house described in this paper was designed to rely on passive heating and cooling strategies for meeting all space conditioning needs. As a result, no conventional residential heating or cooling system was installed. The as-built design consumes 56% less energy than a similar base-case house designed to meet the minimum HERS/MEC requirements. Had the effects of window screens on reducing solar gains been properly modeled resulting in more wall and floor insulation being installed, the Tierra house could have performed 70% better than the base-case house.

8. ACKNOWLEDGEMENTS

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